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NONLINEAR ACOUSTICS: PROPAGATION IN A PERIODIC WAVEGUIDE, SCATTERING OF SOUND BY SOUND, PROPAGATION THROUGH A THREE-LAYER FLUID, AND NONLINEARITY PARAMETERS OF SEA WATER

Third Annual Summary Report under Grant N00014-89-J-1109

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13. ABSTRACT (Maximum 200 words)

Research on nonlinear acoustics has been carried out during the 12-month period ending 30 September 1991. Progress on four primary projects (A-D) is as follows: (A)Airborne acoustic Bloch waves in a periodic waveguide: Both theoretical and experimental work was done on (1)effect of modifying the structure to double the periodicity length of the waveguide, (2)propagation of narrowband Bloch wave pulses, and (3)energy transport velocity and group velocity of Bloch waves. (B)Scattering of sound by sound: Propagation curves and beam patterns were measured to investigate finger radiation, which is a degenerate form of sound scattered by sound. The results confirmed some theoretical predictions but cast doubt on others. Classical crossed beam measurements were begun, but results so far are inconclusive. (C)Finite-amplitude waves in a three-layer fluid: A high precision positioning system was designed and built for experiments to be done in a water tank. Theoretical work was also started. (D)Properties of sea water and fresh water for finite-amplitude wave calculations: Pressure, temperature, and salinity dependence were obtained for the coefficient of nonlinearity β and a related quantity. Miscellaneous projects included ellipsoidal focusing of sound in air.

14. SUBJECT TERMS
nonlinear acoustics; Bloch waves; periodic waveguide; three-layer medium; finger radiation; coefficient of nonlinearity; scattering of sound by sound; ellipsoidal focusing

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1. INTRODUCTION

The research carried out under Grant N00014-89-J-1109, which began 1 October 1988 and is the successor to Contract N00014-84-K-0574, is primarily in the field of nonlinear acoustics. The broad goal is to determine the laws of behavior of finite-amplitude sound waves, especially to find generalizations of the known laws of linear acoustics. This report is the third annual report under the Grant and covers the 12-month period ending 30 September 1991. The previous report (second annual report[1]) is referred to herein as 90-6.*

The following persons participated in the research.

Graduate students

C. E. Bradley, M.S. student in Mechanical Engineering; awarded M.S. degree December 1990. Ph.D. student beginning January 1991.

J. A. Ten Cate, Ph.D. student in Mechanical Engineering.

Y. Yazdi, M.S. student in Electrical and Computer Engineering.

Senior personnel

F. D. Cotaras, Consultant, Defence Research Establishment Atlantic, Dartmouth, Nova Scotia, Canada

M. F. Hamilton,† Mechanical Engineering Department, The University of Texas at Austin

C. L. Morfey, Visiting Research Fellow, on leave from Institute of Sound and Vibration Research, University of Southampton, England

W. M. Wright, Consultant, Physics Department, Kalamazoo College, Michigan

D. T. Blackstock, Principal Investigator

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*Numbers given in this style refer to items in the Chronological Bibliography given at the end of this report, e.g., 90-6 means the sixth entry in the list for 1990.

†Hamilton received no direct support from the Grant. However, he is co-supervisor of Ten Cate's Ph.D. research, which is described in Project B below.

2. PROJECTS

The following projects were active during the report period.

A. Propagation in a Periodic Waveguide

B. Scattering of Sound by Sound

C. Finite-Amplitude Waves in a Three-Layer Fluid

D. Properties of Sea Water and Fresh Water for Finite-Amplitude Wave Calculations

E. Miscellaneous

2.1 Propagation in a Periodic Waveguide

Previously reported on Bradley's project were theoretical and experimental results for both linear and nonlinear acoustic Bloch wave propagation in a periodic waveguide under time harmonic excitation (89-6, 90-4). The periodic waveguide under study is a rigid, air-filled, rectangular duct which is loaded at regular intervals with rigidly terminated rectangular side branches (90-11, 91-4). This year Bradley explored three new areas:

1. The effect of doubling the periodicity length of the structure by alternating the depth of the side branches.
2. The propagation of narrowband Bloch wave pulses.
3. The velocity of energy transport and group velocity of acoustic Bloch waves.

Doubling the periodicity length produces interesting changes in the stopband structure. Recall that stopbands are the spectral regions associated with strongly attenuated Bloch waves (90-11, 91-4). So-called Bragg stopbands occur in the vicinity of the Bragg frequencies $\omega = n\pi c_0/h$, where c_0 is the lossless small signal sound speed, h is the periodicity length, and n is an integer. Another species of stopband occurs at the resonance frequencies of the side branches. If the depth of every other side branch is changed by any fixed amount, the periodicity length doubles ($h \rightarrow 2h$), and the Bragg frequencies are cut in half; that is, a new set of Bragg stopbands appear. In addition, there are *two* sets of side branch resonance frequencies. After a Bloch dispersion relation was derived for such a waveguide, a dispersion measurement was performed for a guide having alternating side branch depths of 31.8 mm and 38.1 mm. When end corrections are added, these depths correspond to resonance frequencies of 2.4 kHz and 2.0 kHz, respectively. Figure 2.1 shows that, in general, theory and experiment agree very well, and in particular that stopbands occur at *both* side branch resonance frequencies as well as at the Bragg frequencies. The periodicity of the structure can, in principle, be increased to nh to generate n tunable side branch

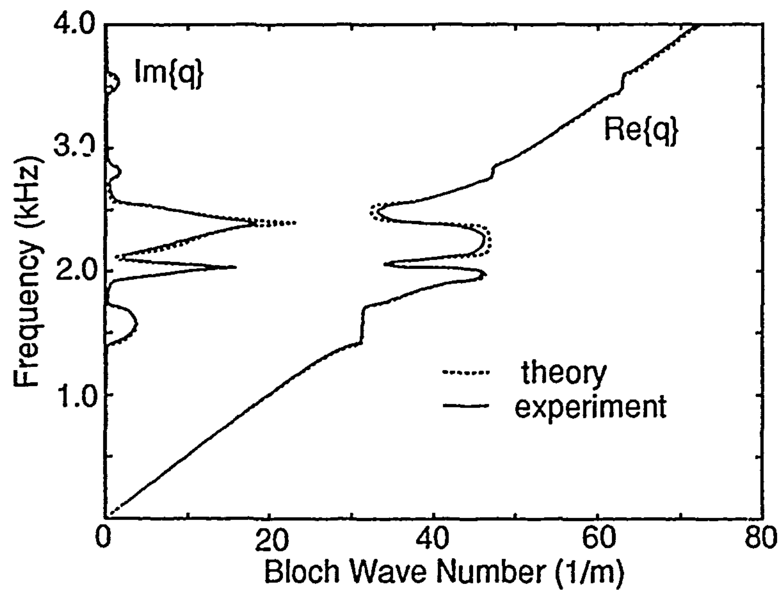

FIGURE 2.1
Theoretical and Experimental Bloch Wave Dispersion Curve for a Periodic Waveguide with Alternating Side Branch Depths of 38.1 mm and 31.8 mm. The Side Branch Resonance Frequencies are Roughly 2.0 kHz and 2.4 kHz, and the Bragg Frequencies are Roughly 800 Hz, 1.6 kHz, 2.8 kHz, and 3.5 kHz.

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resonance stopbands. Such a configuration may be useful to selectively suppress noise propagation in ducts.

Narrowband Bloch wave pulse propagation may be treated by noting the similarity between a Bloch wave of Bloch wave number $q(\omega)$ and a conventional wave of wave number $k = q(\omega)$. The problem of propagation of an arbitrary wave in a periodic medium may be solved by first considering the propagation of the wave in a conventional medium having dispersion and acoustic impedance given by $k = q(\omega)$ and $Z_a = Z_{Ba}(\omega)$, respectively. Here Z_{Ba} is the Bloch acoustic impedance (see 90-4, Sec. 2.1). If the frequency domain solution of the conventional wave problem is $p = \chi(\omega, z)$, the solution of the Bloch wave problem is

$$p(\omega, z) = \psi(\omega, z) * \sum_{n=-\infty}^{+\infty} \delta(z - nh)\chi(\omega, z),$$

where $\psi(\omega, z)$ is the cell wave function (see 90-4, Eq. (2.2)). We may therefore concentrate on the conventional wave problem; the Bloch wave solution can always be recovered by application of the operator $\psi(\omega, z) * \sum \delta(z - nh)$. The equation governing the evolution of the envelope $A(z, t)$ of an arbitrarily modulated carrier of frequency ω_0 is found to be

$$\frac{\partial A}{\partial z} + \frac{1}{c_{gr}}\frac{\partial A}{\partial t} + \sum_{n=2} \frac{1}{n!} j^{n-1} q^{(n)}_{(\omega_0)} \frac{\partial^n A}{\partial t^n} = 0, \tag{2.1}$$

where $q^{(n)}_{(\omega_0)} = d^n q/d\omega^n|_{\omega=\omega_0}$ and $c_{gr} = d\omega/d\mathrm{Re}\{q\}$ is the group velocity. The first two terms represent nondistorting envelope propagation (at the group velocity) and the terms in the sum are envelope distortion terms. A scaling analysis of Eq. (2.1) shows that the n^{th} term in the series can be neglected, provided

$$\frac{z}{h} \ll \frac{z^{(n)}_{(\omega_0)}}{h} = \frac{n!}{2^n}\left[\left.\frac{d^n q}{d\omega^n}\right|_{\omega=\omega_0}\right]^{-1} \frac{(\omega_0\tau_0)^n}{\omega_0^n} = \frac{n!}{2^n}\frac{1}{q^{(n)}_{(\omega_0)}}\frac{(\pi L)^n}{\omega_0^n},$$

where τ_0 is the characteristic time scale of the envelope function and $L = 2\tau_0/(\omega_0/2\pi)$ is the number of carrier cycles in the pulse. For a given initial envelope function and carrier frequency, then, the characteristic distances $z^{(n)}_{(\omega_0)}$ divide the propagation path into a series of zones. To accurately predict the envelope function in the n^{th} zone, we must retain n pulse distortion terms in Eq. (2.1); the remainder may safely be discarded.

Bradley's motivation for studying the velocity of energy transport v_E by acoustic Bloch waves was simply to verify that v_E is the same as the group velocity c_{gr}. He found, however, that the two velocities are not the same (91-2). The velocity of energy transport is the ratio of the time average intensity to the time average energy density. When the energy transport velocity is calculated at the center of the waveguide sections (midway between side branches), we find

$$v_E = c_0 \frac{1 - |g/f|^2}{1 + |g/f|^2},$$

where f and g are the complex amplitudes of the forward and backward traveling plane waves that make up the Bloch wave (90-4, Sec. 2.1). Figure 2.2, which compares theoretical predictions of v_E and c_{gr} for the case of lossless propagation, shows that

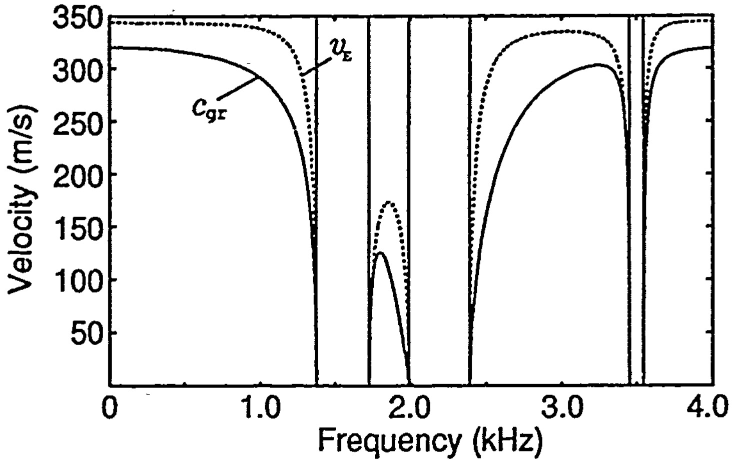

FIGURE 2.2
Theoretical Predictions of the Lossless Bloch Wave Energy Transport Velocity and Group Velocity.

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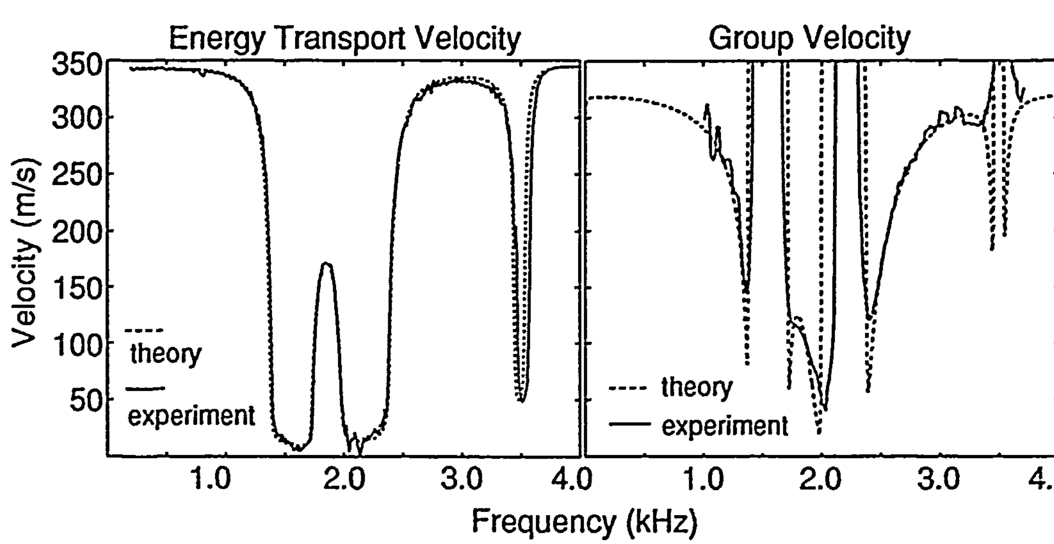

FIGURE 2.3
Lossy Theoretical and Experimental Values of the Bloch Wave Energy Transport Velocity and Group Velocity.

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they differ, a surprising result in terms of classical wave theory. The reason for the difference was found by performing a second analysis using a definition of the energy density which includes the acoustic energy in the side branches. Such a definition of energy density gives the "desired" result, that is, $v_E = c_{gr}$, but does not make physical sense. The side branch energy should not be included in the energy density calculation because it is *stagnant* and does not contribute to the energy flow. The velocity of the group is *less* than the energy transport velocity because the stagnant side branch energy must be deposited by the leading edge of the pulse and recovered by the trailing edge. Figure 2.3 shows a measurement of the energy transport and group velocities and provides a comparison with predictions based on the dissipative theory. While theoretical and experimental values of the group velocity show poor agreement in the vicinity of stopbands, the agreement in the passbands is quite good. Theoretical and experimental values of the energy transport velocity show excellent agreement and are seen to differ significantly from the group velocity.

2.2 Scattering of Sound by Sound

Ten Cate's task is to measure the scattering of sound by sound and to compare his results with predictions obtained by the Tjøttas and their colleagues. He is nearing the end of the experiments and is beginning to write his dissertation. The work since the last report (90-4, Sec. 2.2) has three parts:

1. preliminary setup and testing,
2. "degenerate" scattering of sound by sound experiments, and
3. "classical" scattering of sound by sound experiments.

A description of the tank facility is given in last year's report (90-4, Sec. 2.2).

Most of the preliminary work was devoted to software development for the computer controlled experiments of parts 2 and 3. The central software is National Instrument's LabVIEW™, run on a Mac II computer. Numerous subprograms or virtual instruments (VIs) had to be written before experiments could easily be set up and performed. For example, although LabVIEW™ has an FFT and numerous window functions, it is up to the user to organize and connect them to best suit the experiment. Two major groups of VIs were programmed, one controlling motion along various axes of the positioning apparatus, and the other for performing the necessary signal processing. Running an experiment is now very simple. One needs only to plan the basic steps of the experiment, assemble the appropriate modules corresponding to these steps, try the experiment, and reprogram if necessary.

In order to discuss parts 2 and 3, we must first define certain terms. "Classical" scattering of sound by sound results from the interaction of two primary beams that are produced by separate sources and that intersect at a nonzero angle. The scattered sound is secondary radiation in the form of sum and difference frequency beams that emerge at angles different from those of the primary beams. A significant property of the scattered sound is that it exists outside the zone of interaction of the two primary beams. A degenerate form of scattering occurs when a single source emits sound at a single frequency. The primary sound now interacts with itself, and the zone of interaction is the entire primary field, which includes the sidelobes as well as the main lobe and the nearfield. Each higher harmonic beam pattern exhibits two sets of lobes: (1) the main lobe and sidelobes at the same angles as those of the primary pattern, and (2) additional sidelobes, called *fingers*, which have no counterpart in the primary pattern. Because they exist outside the zone of interaction, fingers are considered to be scattered sound. Their asymptotic decrease with distance is predicted to be $1/r$, the same as ordinary spherical spreading. The lobes matching the primary pattern, which, for want of a better term we shall call *ordinary lobes*, are more complicated. They are composed of scattered radiation (like that responsible for the fingers) and product radiation, so-called because it corresponds to multiplying the primary radiation by itself one or more times. Product radiation is predicted to diminish asymptotically as $(\ln r)/r$. Ordinary lobes are therefore expected to diminish with distance in a complicated way that includes both $1/r$ and $(\ln r)/r$ contributions. Eventually, at very great distances, the $(\ln r)/r$ contribution is expected to dominate.

Ten Cate has made careful measurements of the fingers of several different sources. Figure 2.4 shows transverse, half-beam patterns measured in a strong source experiment. The source was a 12 mm radius piston, driven at 1 MHz, and the range was about three Rayleigh distances. The first four harmonics are presented. The data are shown as squares, and the theoretical predictions as solid curves. Note that the number of fingers between each pair of ordinary lobes is one for the second harmonic, two for the third harmonic, and three for the fourth harmonic. The theoretical predictions were generated from the frequency-domain Bergen KZK program for collinear interaction.[2] Overall the results show excellent agreement. The slight mismatch that begins to appear 100 mm off axis (corresponding to an angle of about 8°) is due to incipient inaccuracy of the KZK equation as the observation point departs from the paraxial region.

The predicted difference between the asymptotic decays of the fingers and the ordinary lobes has in the past provided hope for distinguishing between scattered radiation and product radiation. In the next series of experiments, Ten Cate attempted to realize this hope by measuring propagation curves for the first finger and the first ordinary sidelobe of the second harmonic radiation. Unfortunately, the predicted decays — $1/r$ for the finger and a mixture of $1/r$, $(\ln r)/r$ and a constant for the ordinary lobe — are so similar that their difference can be expected to become clear only

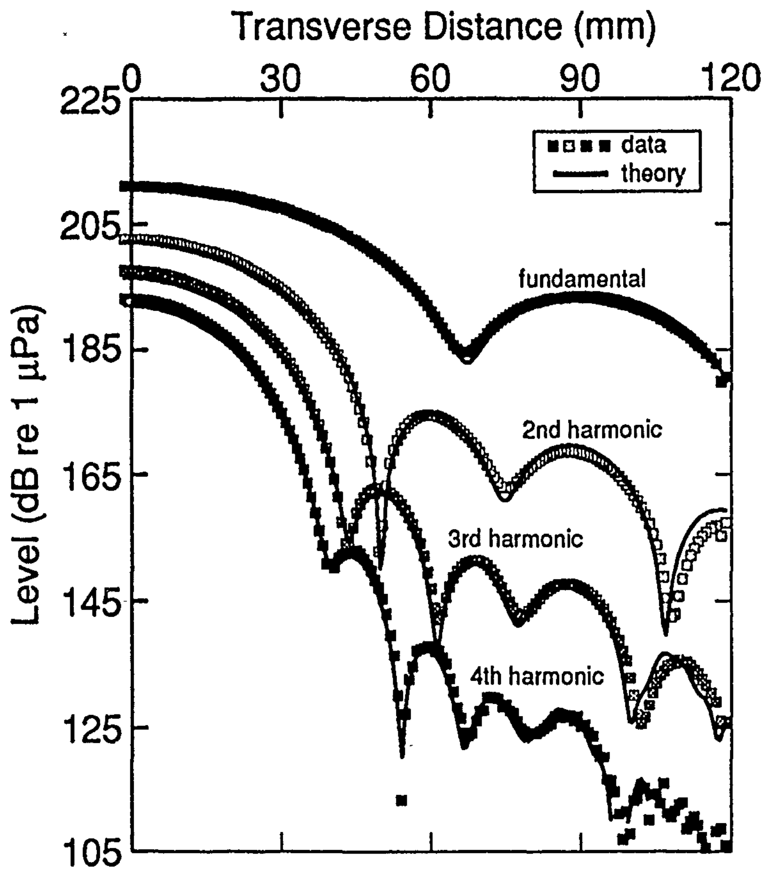

FIGURE 2.4
Beam Patterns of First Four Harmonics in Strong Source Experiment. Fundamental Frequency Is 1 MHz, Piston Radius Is 12 mm, Range Is 894 mm (about 3 Rayleigh Distances). Theoretical Curves Represent Bergen KZK Curves (Ref. 2).

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over an extended propagation range, which moreover must be measured in terms of Rayleigh distances. Accordingly, Ten Cate chose a source with the shortest Rayleigh distance available (about 40 mm): a 2.2 MHz, 3 mm radius source. Given the size of the tank, Ten Cate was able to measure the finger and product sidelobe levels from about 5 to about 25 Rayleigh distances. The decay rates of the two lobes are shown in Figure 2.5. This was a difficult experiment to program and execute, and any attempt to do it without computer-controlled positioning apparatus would have been useless. Once again the Bergen KZK code[2] was used to compute the theoretical curves. The data points by themselves show that the finger and product sidelobes do indeed have different decay rates. Quantitative agreement of theory with the data is excellent for the finger. Alas, agreement is not as good for the product sidelobe, probably because the sidelobe is located at an angle of approximately 11°, a little wide for high accuracy from the parabolic approximation. To remove any question about the accuracy of the parabolic approximation, Ten Cate is planning a similar experiment

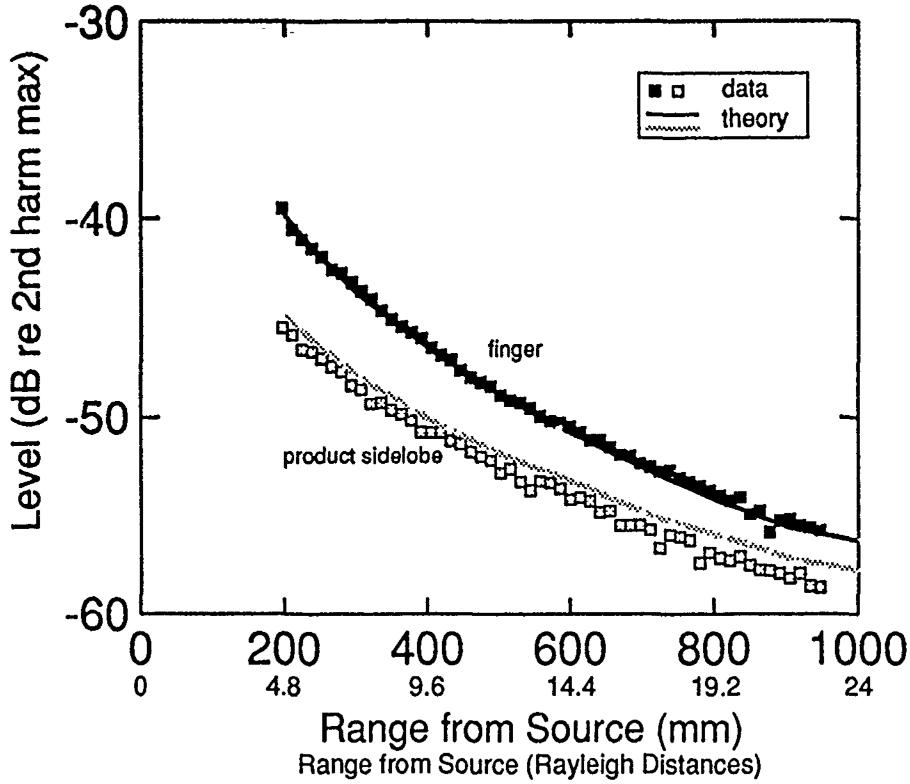

FIGURE 2.5
Decay of Second Harmonic Finger and Product Sidelobe. Fundamental Frequency Is 2.2 MHz, Piston Radius Is 3 mm. Theoretical Curves Represent Bergen KZK Solution (Ref. 2).

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in which the propagation curves of the *main lobe* and first finger will be compared. The main lobe is a member of the product family that always satisfies the parabolic approximation.

Our report of the work on classical scattering of sound by sound begins with disquieting news about the solution Ten Cate had been counting on for his theoretical prediction. This is a quasilinear, lossless, asymptotic solution of a Westervelt-like, inhomogeneous wave equation and requires numerical evaluation.[3] To test the accuracy of the solution, Ten Cate carried out several single-source, single-primary experiments. These were similar to the one for which Fig. 2.4 gives beam patterns, except that the source amplitude was weak in order that the quasilinear assumption be satisfied. Figure 2.6 shows beam patterns for a 1 MHz, 12 mm radius source and the corresponding asymptotic solution. Agreement between theory and experiment is good for the product radiation parts of the beam pattern but poor for the finger radiation parts. For both fingers (at 4° and at 7.5°) not only is the prediction higher than the data, the resolution is unexpectedly poor. Results of other experiments are similar although details of the disagreement vary. Lack of agreement with the data

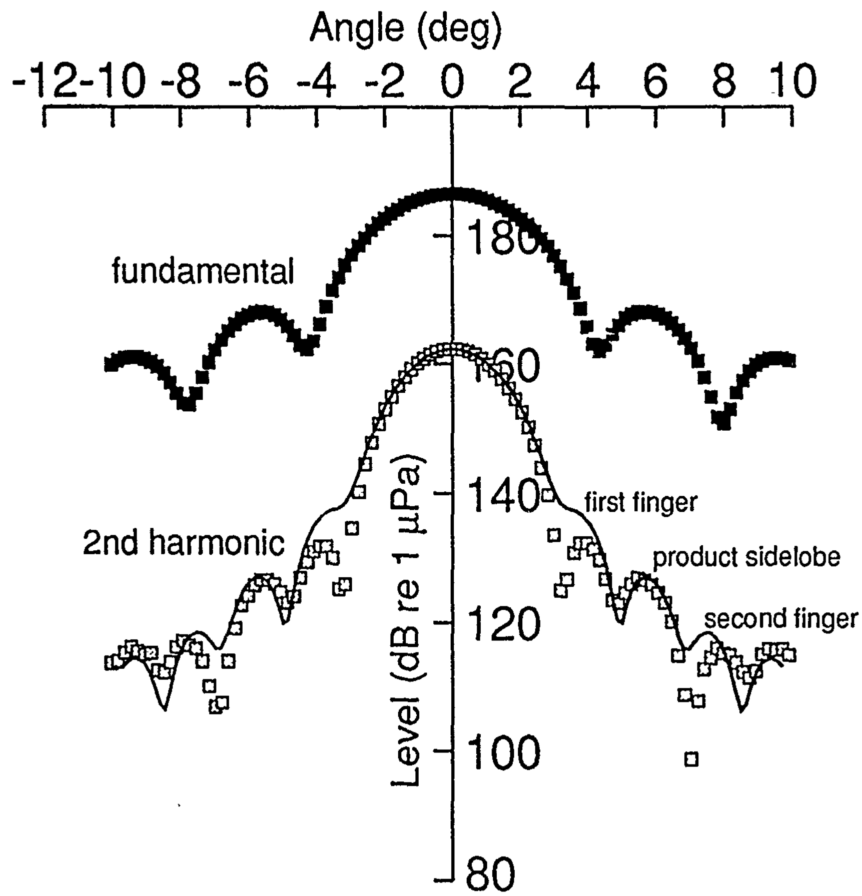

FIGURE 2.6
Beam Patterns of Fundamental and Second Harmonic in Weak Source Experiment. Fundamental Frequency Is 1 MHz, Piston Radius Is 12 mm, Range Is 770.6 mm (about 3 Rayleigh Distances). Theoretical Curve for Second Harmonic Is from Asymptotic Solution (Ref. 4).

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prompted Ten Cate to test the asymptotic solution by comparing it with results from the Bergen KZK program[4] under conditions of overlapping validity. Frequently, but not always, he found the asymptotic solution to give poor predictions of the finger radiation (agreement is satisfactory for the product radiation). The unreliability of the asymptotic solution in describing the finger radiation is a source of real concern, for we had been counting on it to provide theoretical predictions for the classical scattering experiments.

Difficulty with the asymptotic solution, although vexing from our immediate perspective, poses an interesting theoretical question. Why does the solution sometimes give poor predictions of the finger radiation? An answer needs to be found because the solution has already been used as the basis for several papers, including 91-1. Ten Cate is currently looking into this question.

Finally, Ten Cate has performed one preliminary classical scattering experiment. The two sources were a 2 MHz Gaussian piston and a 0.5 MHz circular piston, and the interaction angle was about 30°. Although the results of the experiment were inconclusive, they provided valuable information for planning. The final experiments will be done with great care, and both sources will be circular pistons.

2.3 Finite-Amplitude Waves in a Three-Layer Fluid

This is Yazdi's project. See Fig. 2.7. We wish to determine what happens to a finite-amplitude wave as it travels through fluid 1, encounters fluid 2 of finite thickness, and eventually passes into fluid 3, which is taken to be semi-infinite. The special case in which fluids 1 and 3 are the same will also be considered. The work is intended to be both experimental and theoretical. Because of being heavily occupied with course work during his first year, Yazdi has devoted most of his research effort thus far to design and construction of an apparatus for the experiments.

The apparatus is a new, high precision positioning system. See Figs. 2.8 and 2.9. When completed, the system will be available not only for three-media experiments, but also for general use in the Nonlinear Acoustics Laboratory. The system, which is a scaled-down version of the positioning system used by Ten Cate and located in the Mechanical Engineering Department (see Sec. 2.2 above and also 89-6, Sec. 2.3), allows for computer-controlled positioning of a target or source and has 4 degrees of freedom. Precision positioning is obtained with an open-loop system using microstepping motors. The motors are controlled via the IEEE-488 interface bus already in use in the Laboratory. The positioning system is constructed of modular components in order to make the system easy to modify and/or improve. Because it is a standalone apparatus, i.e., it is not attached to a water tank, it may be used in other, quite

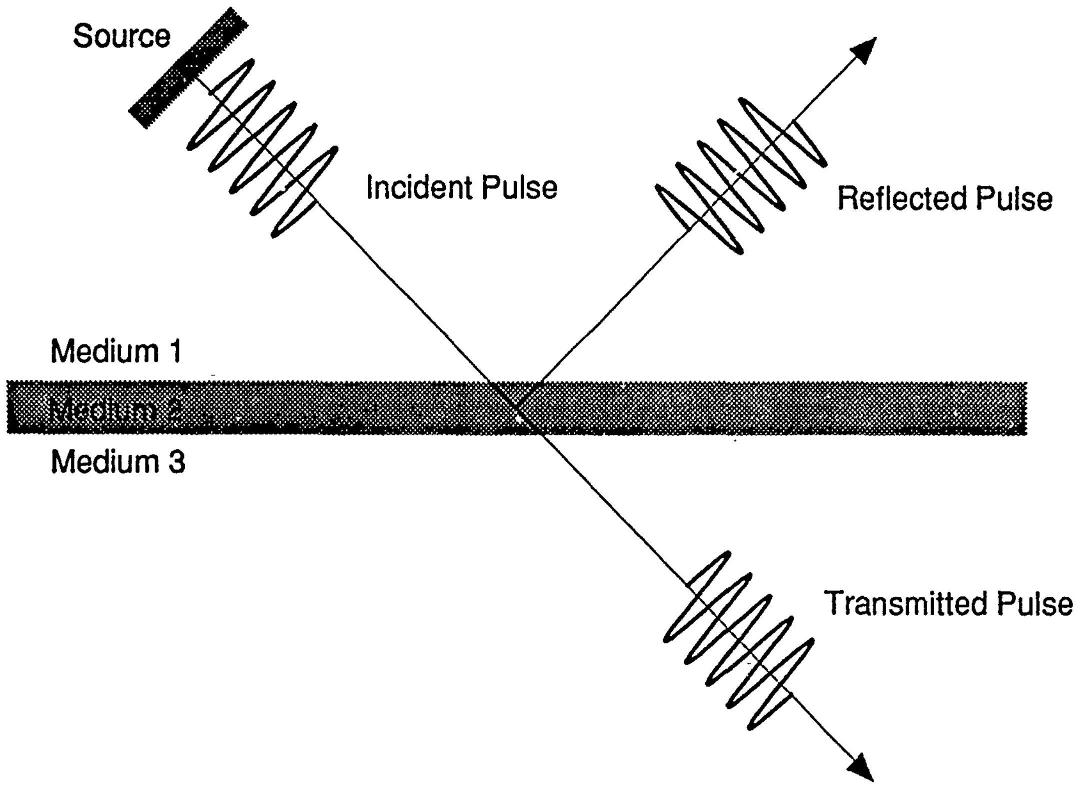

FIGURE 2.7
Three-fluid Problem.

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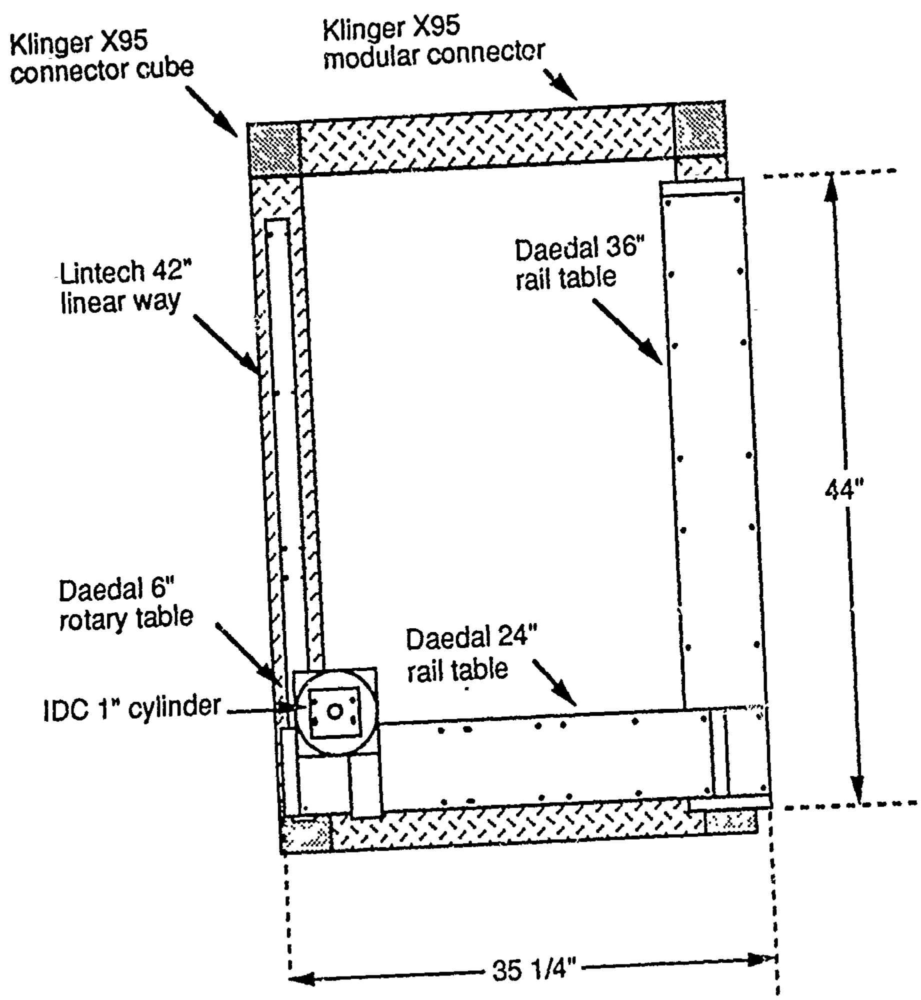

FIGURE 2.8
Top View of Positioning System.

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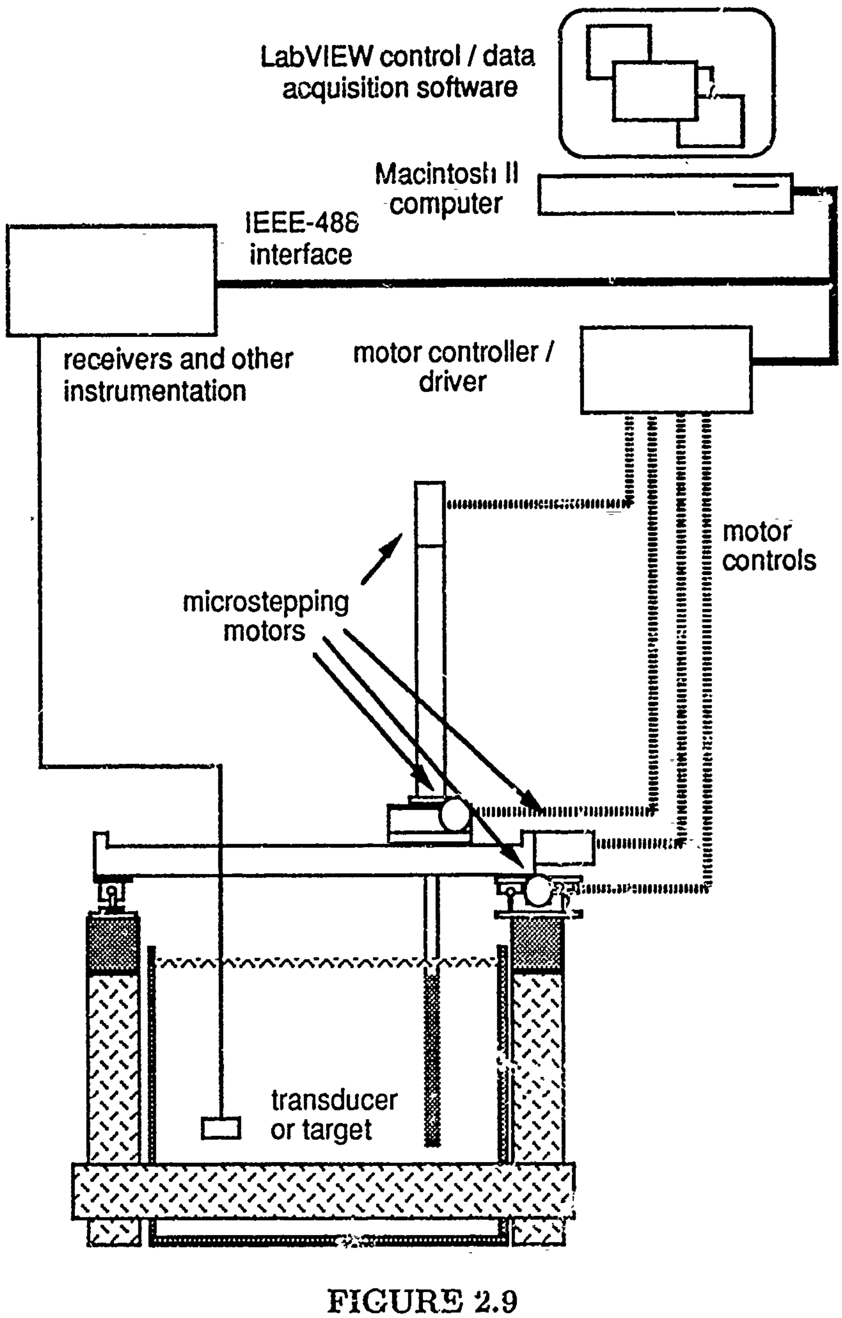

FIGURE 2.9
Motors, Controls, and Driver for Positioning System.

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different applications, for example, experiments on airborne propagation of N waves from sparks. Although the design has been complete for some time, construction has been held up because of the long time needed to acquire some of the components.* It is expected that construction of the positioning system will be complete by the end of the present report period. Testing will begin at that time.

Although Yazdi will not take a course in nonlinear acoustics until the Fall 1991 semester, he has begun some preliminary theoretical work. The simplest case, normal incidence, is being considered first. Initially, the goal will be to confirm the results of F. D. Cotaras (89-1), which are for a single interface. Then the standing wave field resulting from the second interface will be considered. Finally, the transmitted wave in the third medium will be determined. Of particular interest will be how thickness of the middle layer affects the character of the reflected field in fluid 1 and the higher-order harmonics in the transmitted field (fluid 3). Measurements will of course accompany theoretical predictions.

2.4 Properties of Sea Water and Fresh Water for Finite-Amplitude Wave Calculations

The account below is a preliminary draft of a letter to the editor that will soon be submitted by its authors, F. D. Cotaras and C. L. Morfey, to *J. Acoust. Soc. Am.* The present task had its beginnings several years ago when first Morfey[5] and later Cotaras[6] investigated long range underwater propagation of finite-amplitude sound. The task was carried to completion this year. A more complete description of the work in the form of a technical report was in preparation at the time of writing of this report.[7]

Coefficient of Nonlinearity in Fresh Water and Sea Water

by

F. D. Cotaras and C. L. Morfey

In the study of nonlinear acoustic propagation through an inhomogeneous fluid such as sea water, it is helpful to have explicit relations for the acoustic properties of the fluid as a function of temperature, pressure, and salinity. For both fresh water and sea water, several empirical relations give the sound speed c and the density ρ as functions of temperature, pressure, and, in the case of sea water, salinity. We are,

*We are indebted to NIH for providing the motor controller/driver and motors shown in Fig. 2.9.

however, unaware of any similar relations for the coefficient of nonlinearity β. Endo[8] has tabulated β for sea water over a broad range of temperatures and pressures for salinities of 25, 30, 35, and 40 parts per thousand (ppt). For computer implementations of nonlinear propagation through sea water, however, relations with explicit temperature, pressure, and salinity dependence are preferable to tables of values

In this work we develop two relations for β: one for fresh water as a function of temperature, and pressure, and one for sea water as a function of temperature, pressure, and salinity. Endo's tabular values were very useful in checking our results for sea water. We also develop relations for the term $\Lambda \equiv \beta/(\rho c^5)^{1/2}$. The reason for developing separate relations for this term is that it arises as an important variable in nonlinear geometrical acoustics.[9]

The coefficient of nonlinearity is defined as follows: $\beta = 1 + B/2A$, where A and B are the first and second coefficients of the Taylor series expansion of the pressure in terms of the density. (In fresh water at room temperature and atmospheric pressure, β has a value of approximately 3.5.) The quantity B/A may be expressed as follows:[10]

$$\frac{B}{A} = 2\rho c \left(\frac{\partial c}{\partial P}\right)_T + 2\frac{c\alpha T}{C_P}\left(\frac{\partial c}{\partial T}\right)_P \quad , \tag{2.2}$$

where the subscript indicates the variable held constant, and T, α, and C_P are, respectively, the absolute temperature, the coefficient of thermal expansion, and the specific heat at constant pressure. To evaluate this relation, we used published empirical relations as much as possible. Since different empirical relations exist for both c and ρ, we implemented several of them numerically and calculated the absolute difference in β that results from using the different relations. The term that was found to cause the greatest difference is $(\partial c/\partial P)_T$; variations in this term produce an absolute difference in β that is always less than 0.05 and typically less than 0.025.*

Rather than embark on an investigation of the origin of differences in the pressure dependence of the various relations for c in sea water, we simply chose to use the relations from Chen, Millero, and their co-workers[11-15] over those of other workers. The choice was based on uniformity of approach: Chen, Millero, and their co-workers have developed empirical relations not only for c, but also for ρ, α, and C_P. Thus, for sea water, we favored the works of Refs. 11 and 12 for c and ρ, whereas for fresh water, we used the relations in Refs. 13 and 14. To obtain the derivatives of the sound speed, we differentiated the published empirical relations with respect to temperature and pressure. To estimate α, we used an explicit relation for α in sea water from Ref. 12, whereas for fresh water we evaluated $-\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_P$ using the empirical relation for ρ from Ref. 14. For sea water, our estimates of C_P were obtained by summing the estimate of C_P at one atmosphere that is obtained from a relation in Ref. 15 with the

*In this particular case, we were comparing the difference in β that results from using the empirical relations for c in sea water from Lovett[16] with that from Chen and Millero.[11]

contribution from the isothermal integration of

$$-T\int \frac{1}{\rho}\left(\alpha^2 + \left(\frac{\partial \alpha}{\partial T}\right)\right) dP \quad . \tag{2.3}$$

The estimates of α and ρ for Eq. (2.3) were obtained from the appropriate aforementioned references. For fresh water, on the other hand, we used a polynomial fit to a C_P data set.[17]

Our relations for β were obtained as follows: For sea water, Eq. (2.2) was evaluated over the following range: temperature −4° to 40°C, pressure 1 to 800 bar absolute, and salinity 30 to 40 ppt. (Because the low limit of the temperature range of the original relations is 0°C, not −4°C, our relation must be used with caution in the −4° to 0°C region.) The resulting data points were then fitted to a polynomial expression that is fifth order in temperature, third order in pressure, and linear in salinity. The polynomial expression is

$$\beta = \sum_{l,m,n} B_{lmn}(S-35)^l P^m T^n \quad , \tag{2.4}$$

where the salinity S is in ppt, the pressure P is in bars gauge, and the temperature T is in °C. Terms raised to the 0 power are taken as unity for all possible input values, including 0. The coefficients B_{lmn} are listed in Table 2.1. The absolute difference between the polynomial fit in Eq. (2.4) and the direct calculation over the cited range is less than 10^{-3}. Similarly for fresh water, Eq. (2.2) was evaluated over the temperature range 0° to 100°C and the pressure range 1 to 800 bar absolute. A polynomial fit of the same order in temperature and pressure was then obtained that yielded absolute errors of the same size. The relation is

$$\beta^{\text{fresh}} = \sum_{l=0,m,n} B_{lmn}^{\text{fresh}} P^m T^n \quad , \tag{2.5}$$

and the coefficients B_{lmn}^{fresh} are listed in Table 2.1.

Polynomial fits that are valid over the same range of temperature, pressure, and salinity were also developed directly for $\Lambda \equiv \beta/(\rho c^5)^{1/2}$ for both sea and fresh water. The maximium absolute errors in these fits are 0.001 and 0.002 for sea water and fresh water, respectively. The relations are shown in Eqs. (2.6) and (2.7) and the coefficients are listed in Table 2.2:

$$\Lambda = \left(\sum_{l,m,n} L_{lmn}(S-35)^l P^m T^n\right) \times 10^{-9} \quad , \tag{2.6}$$

$$\Lambda^{\text{fresh}} = \left(\sum_{l=0,m,n} L_{lmn}^{\text{fresh}} P^m T^n\right) \times 10^{-9} \quad . \tag{2.7}$$

TABLE 2.1
Coefficients in Polynomial Expression for β.

l	m	n	B_{lmn}^{fresh}	B_{lmn}
0	0	0	+3.122127	+3.44166
0	0	1	+0.0262768	+0.0176224
0	0	2	−0.000439164	−0.000478735
0	0	3	+0.00000520032	+0.0000129976
0	0	4	-3.07095×10^{-8}	-1.85398×10^{-7}
0	0	5	$+6.12344 \times 10^{-11}$	$+3.36832 \times 10^{-10}$
0	1	0	+0.00139138	+0.00104125
0	1	1	−0.000051128	−0.0000457645
0	1	2	$+7.40662 \times 10^{-7}$	$+5.84691 \times 10^{-7}$
0	1	3	-6.41226×10^{-9}	$+5.16276 \times 10^{-9}$
0	1	4	$+2.53274 \times 10^{-11}$	-3.84942×10^{-11}
0	2	0	-2.15517×10^{-7}	-1.69183×10^{-7}
0	2	1	$+3.45228 \times 10^{-9}$	$+1.69021 \times 10^{-8}$
0	2	2	$+1.44653 \times 10^{-10}$	-3.37325×10^{-10}
0	2	3	-2.82686×10^{-12}	-3.82096×10^{-12}
0	2	4	$+1.26217 \times 10^{-14}$	$+4.52996 \times 10^{-14}$
0	3	0	-1.12614×10^{-10}	-6.58146×10^{-11}
0	3	1	$+4.51141 \times 10^{-12}$	$+6.60716 \times 10^{-12}$
0	3	2	-2.91434×10^{-14}	-1.63621×10^{-13}
1	0	0		+0.00833572
1	0	1		−0.000232407
1	0	2		+0.00000107536
1	1	0		−0.0000115765
1	1	1		$+7.2387 \times 10^{-9}$
1	1	2		$+1.0786 \times 10^{-8}$
1	2	0		$+3.2689 \times 10^{-9}$
1	2	1		$+4.6156 \times 10^{-10}$
1	2	2		-1.86744×10^{-11}

TABLE 2.2

Coefficients in Polynomial Expression for Λ.

l	m	n	L_{lmn}^{fresh}	L_{lmn}
0	0	0	$+1.340649$	$+1.34255$
0	0	1	-0.00123676	-0.00369707
0	0	2	-0.0000219506	-0.0000454961
0	0	3	$+7.51912 \times 10^{-7}$	$+0.00000411388$
0	0	4	-2.82344×10^{-9}	-7.30211×10^{-8}
0	0	5	-5.22167×10^{-12}	$+2.49154 \times 10^{-10}$
0	1	0	$+0.000197704$	-2.88818×10^{-7}
0	1	1	-0.0000256345	-0.0000191962
0	1	2	$+4.70095 \times 10^{-7}$	$+4.28444 \times 10^{-7}$
0	1	3	-4.83161×10^{-9}	-4.12041×10^{-9}
0	1	4	$+1.90758 \times 10^{-11}$	$+4.36867 \times 10^{-11}$
0	2	0	-2.69563×10^{-7}	-1.43851×10^{-7}
0	2	1	$+1.46666 \times 10^{-8}$	$+1.65626 \times 10^{-8}$
0	2	2	-1.99597×10^{-10}	-3.94804×10^{-10}
0	2	3	$+1.59563 \times 10^{-12}$	$+2.14739 \times 10^{-12}$
0	2	4	-5.86015×10^{-15}	-1.49805×10^{-14}
0	3	0	$+4.01117 \times 10^{-11}$	$+2.48433 \times 10^{-11}$
0	3	1	-1.60177×10^{-12}	-2.5426×10^{-12}
0	3	2	$+8.41646 \times 10^{-15}$	$+4.69605 \times 10^{-14}$
1	0	0		-0.000374879
1	0	1		-0.0000614364
1	0	2		$+4.68875 \times 10^{-7}$
1	1	0		-0.00000518082
1	1	1		$+1.53554 \times 10^{-7}$
1	1	2		$+9.56226 \times 10^{-10}$
1	2	0		$+2.92378 \times 10^{-9}$
1	2	1		$+2.13857 \times 10^{-11}$
1	2	2		-3.87438×10^{-12}

2.5 Miscellaneous

The project on ellipsoidal focusing did not benefit from student research this year but continued as a specific interest of Blackstock and Wright. For earlier reports see 89-6, Sec. 2.4, and 90-4, Sec. 2.4. Wright augmented his earlier work with off-axis waveform measurements in the focal plane of the reflector. A draft of a journal article on the ellipsoidal focusing measurements was completed. In recent theoretical work done under ONR Grant N00014-89-J-1003, Hamilton[18] has developed an impulse response function for the reflected field on the axis of an ellipsoidal mirror. Although the analysis is restricted to small signals, we expect to be able to use it for qualitative interpretation of our experimental measurements. Both Hamilton[19] and Blackstock and Wright[20] plan to report their results at the Fall 1991 Meeting of the Acoustical Society of America in Houston.

Three other miscellaneous items are as follows. Hamilton (supported under ONR Grant N00014-89-J-1003) and Blackstock collaborated on a small investigation on linearity of the momentum equation for plane progressive waves (90-9). Blackstock gave the Rayleigh Lecture at the 1990 ASME Winter Annual Meeting (90-10); the topic was nonlinear acoustics and the approach was historical. Finally, some work on reflection and transmission of spherical waves at a concentric spherical interface was presented by Blackstock and Morfey at the Spring 1991 Meeting of the Acoustical Society of America in Baltimore (91-3).

3. SUMMARY

Research during the current report period, 1 October 1990 – 30 September 1991, has been devoted largely to four projects: (A) propagation in a periodic waveguide, (B) scattering of sound by sound, (C) finite-amplitude waves in a three-layer fluid, and (D) properties of sea water and fresh water for finite-amplitude wave calculations. Project A is a combined theoretical and experimental study of acoustical Bloch waves in a rectangular, air-filled waveguide that is periodically loaded with rigidly terminated side branches. Three new areas were explored this year: effect of alternating the depth of the side branches to achieve a structure with twice the periodicity length, propagation of narrowband Bloch wave pulses, and energy transport velocity and group velocity of acoustic Bloch waves. A great deal of experimental work was done under Project B. Many measurements were made of so-called finger radiation (extra lobes in the beam patterns of the harmonic components that are generated when a single source is driven at a single frequency), which is a degenerate form of sound scattered by sound. Very carefully measured beam patterns and propagation curves confirm some theoretical predictions of the finger radiation but cast doubt on others. Crossed beam experiments (two sources, two frequencies) were begun to try to measure classical scattering of sound by sound. Project C is just beginning. Most of the work on Project C so far has been on design and construction of a high precision positioning system intended primarily for ultrasonic measurements in a small water tank. Project D represents the completion of work begun several years ago to obtain the pressure, temperature, and salinity dependence of certain quantities that are commonly used in computing the propagation of finite-amplitude waves in the ocean and in fresh water. Finally, miscellaneous projects include work on ellipsoidal focusing of sound in air and various topics on which papers were presented during the year.

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1988–1991
Grant N00014-89-J-1109
and
Predecessor Contract N00014-84-K-0574 (ended 9-30-88)

Code			ONR Grant/Contract		
B	=	chapter in a book	1109	=	N00014-89-J-1109, began 10-1-88
J	=	journal publication			
JS	=	submitted for journal publication	0574	=	N00014-84-K-0574, ended 12-31-88
O	=	oral presentation			
P	=	paper in a proceedings			
T	=	thesis or dissertation	0867	=	N00014-75-C-0867 ended 8-31-84
TR	=	technical report			

1988

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1989

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1990

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